

METHODS AND SYSTEMS FOR REACTIVELY COMPENSATING
—MAGNETIC CURRENT LOOPS—

AN APPLICATION FOR
UNITED STATES LETTERS PATENT

By

Leandra Vicci
Siler City, North Carolina

Wayne D. Dettloff
Cary, North Carolina

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Karen S. Flynn

Description

METHODS AND SYSTEMS FOR REACTIVELY COMPENSATING MAGNETIC CURRENT LOOPS

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Related Application Information

This application claims the benefit of United States Provisional Patent Application No. 60/169,726, filed December 8, 1999, the disclosure of which is incorporated herein by reference in its entirety.

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Technical Field

The present invention relates to methods and systems for reactively compensating magnetic current loops. More particularly, the present invention relates to methods and systems for adding reactive compensation to 15 magnetic current loops to provide magnitude and phase uniformity along the magnetic current loops.

Related Art

Magnetic current loops are commonly used to transfer power and 20 information between microelectronic devices. For example, in one system, a card reader, which includes one or more magnetic current loops, generates a magnetic field by energizing the magnetic current loops. A card, which includes a printed circuit board and one or more magnetic current loops,

receives power from the card reader through its magnetic current loops when the card is brought into close proximity to the reader. The card may also receive an information signal from the reader that is modulated on the power signal. The information signal may be a query to which the card responds by transmitting its own information signal to the reader. The reader receives the response from the card and an action takes place, such as the opening of a gate, the storing of identification information, etc.

Systems in which a microelectronic circuit receives power from a magnetic field can be used in warehouses so that a pallet of goods having an inductively-powered identification circuit need only be brought within the communication range of a reader in order to track the location of the goods in the warehouse. Such magnetic-current-loop-based communication systems provide a distinct advantage over conventional systems in which bar codes and bar code readers are used to track goods. Using bar codes and bar code readers to track goods is difficult because a bar code must be brought into very close proximity, e.g., within a few inches, to a bar code reader in order for the information to be read. In addition, bar codes must be read in a specified order and orientation and carry only limited information. Thus, magnetic-current-loop based communication systems provide a significant advantage over conventional bar code systems.

One goal of magnetic-current-loop-based communication systems is to increase the distance at which an electronic circuit can be powered by and communicate with the reader. For instance, in the warehouse example discussed above, it may be desirable for an identification circuit associated with a pallet of goods to be powered by and communicate with a reader at a

distance of about 3 meters or more from the reader. One way to increase the communication and powering distance in such a system is to increase the power transmitted by the reader. However, one problem with increasing the power is that regulatory agencies, such as the Federal Communications
5 Commission in the United States, place restrictions on radiated power at given frequencies. These restrictions have prevented conventional systems from achieving the desired communications and powering distance.

In the United States, some Federal Communications Commission limits are based on radiated power at a distance of 30 meters from the source. One
10 frequency range in which the restrictions on radiated power are less stringent than restrictions for other frequency ranges is the range centered at 13.56 MHz. For example, the FCC allows 100 microvolts per meter in the range of 13.56 MHz \pm 7 kHz and only 30 microvolts per meter for frequencies immediately outside of this range. Accordingly, 13.56 MHz is commonly used
15 for magnetic-current-loop-based communication systems. However, even with these decreased restrictions, it has been difficult to design a system that extends the magnetic field to the desired distance without violating regulatory standards.

Exemplary systems capable of achieving the desired goals of
20 increasing the communication and powering distance without violating regulatory standards are described in International Publication No. WO 99/60512, published November 25, 1999, and United States Provisional Patent Application No. 60/169,726, filed December 8, 1999, the disclosure of each of which is incorporated herein by reference in its entirety. The systems
25 described in the above-referenced patent applications include multiple

magnetic current loops positioned adjacent to each other and separately driven by in-phase current sources. Driving adjacent current loops with in-phase current sources produces a strong near field and a weak far field. As used herein, a near field refers to an electromagnetic field that is located 5 within about 1 wavelength of the source of the electromagnetic field and a far field refers to an electromagnetic field at a distance of more than about 1 wavelength from the source.

A single magnetic dipole produces undesirably high far field radiation. For example, at a distance far from a single magnetic dipole, the dipole 10 appears as a point source. The electric field strength of the single magnetic dipole decreases proportionally to $1/R^2$, where R is the distance from the single magnetic dipole. Because the field strength only decreases at a rate proportional to $1/R^2$, single magnetic dipoles are limited in the amount of transmitter power that can be applied.

15 The system described in the above-referenced patent applications relies on cancellation of the dipole effects of individual magnetic current loops to produce only quadrupole and higher order fields at distances far from the source. For example, if two identical magnetic current loops are placed adjacent to each other and driven in opposite directions, the dipole fields 20 cancel at a distance far from the source. The remaining far field is a quadrupole field that decreases in strength at a rate of $1/R^3$. Similarly, using four identical, adjacent magnetic current loops driven in the appropriate directions results in cancellation of the dipole and quadrupole fields to produce an octupole field that decreases at a rate of $1/R^4$ in strength as one 25 moves away from the source. Thus, the goal of the system described in the

above-referenced patent applications is to produce only higher order fields at distances far from the current loop sources.

One way to achieve magnitude and phase uniformity in magnetic current loop arrays is to divide each magnetic current loop into N sections and
5 to separately drive each of the N sections with its own current source.

However, such a system is complex and difficult to implement because it requires synchronization and uniformity among current sources. Accordingly, there exists a long-felt need for methods and systems for providing magnitude and phase uniformity of currents flowing through current loops in a magnetic
10 current loop system.

Disclosure of the Invention

According to one aspect, the present invention includes methods and systems for providing reactive compensation for magnetic current loops in a
15 magnetic-current-loop-based communication system. For example, each current loop in a magnetic current loop system may be divided into a number of segments. A single current source may be used to drive all of the magnetic current loops in the system. Reactive compensation may be provided for each segment so that the reactive compensation cancels the series reactance
20 of each segment. Because the reactive compensation effectively cancels the reactance of each segment of the current loop, the phase delay along each current loop is nearly zero. As a result, the magnitude and phase of the current along each current loop will be nearly uniform at any given time. In addition, since adjacent loops are preferably divided and reactively
25 compensated in a similar manner, lower-order fields resulting from inexact

compensation cancel. Since the dipole fields of such current loops cancel at distances far from the current loops, only quadrupole and higher order fields remain, which decrease rapidly as the distance from the source increases. As a result, near fields can be extended by increasing power without violating 5 regulatory standards and without requiring unnecessarily complex drive electronics. The increased near fields result in a greater communication distance between readers and identification devices.

Accordingly, it is an object of the present invention to provide methods and systems for reactively compensating magnetic current loops in a manner 10 that allows generation of strong near fields and weak far fields.

It is yet another object of the invention to provide a reader for a magnetic-current-loop-based communication system that includes reactively compensated current loops according to an embodiment of the invention.

Some of the objects of the invention having been stated hereinabove, 15 other objects will be evident as the description proceeds, when taken in connection with the accompanying drawings as best described hereinbelow.

Brief Description of the Drawings

Preferred embodiments of the present invention will now be explained 20 with reference to the accompanying drawings of which:

Figure 1 is a schematic diagram of a magnetic current loop driven by a current source;

Figure 2 is a schematic diagram of a transmission line model of the magnetic current loop illustrated in Figure 1;

Figure 3 is a schematic diagram illustrating a ladder network used to model the magnetic current loop of Figure 1;

Figure 4 is a schematic diagram of the ladder network in Figure 3 in which shunt loss is ignored;

5 Figure 5 is a schematic diagram of a magnetic current loop divided into a plurality of sections including reactive compensation for each section according to an embodiment of the present invention;

Figure 6 is a schematic diagram of a ladder network used to model the magnetic current loop of Figure 5, in which the series reactance is cancelled

10 by the reactive compensation according to an embodiment of the present invention;

Figure 7(a) is a perspective view of first and second magnetic current loops including reactive compensation according to an embodiment of the present invention;

15 Figure 7(b) is a perspective view of first, second, and third magnetic current loops having reactive compensation according to an embodiment of the present invention;

Figure 8 is a schematic diagram illustrating a circuit model of a magnetic current loop in which capacitive reactance is chosen slightly off resonance according to an alternative embodiment of the present invention;
20 and

Figure 9 is a schematic diagram of a reader including reactively compensated magnetic current loops according to an embodiment of the present invention.

Disclosure of the Invention

Figure 1 illustrates a magnetic current loop to which reactive compensation according to embodiments of the present invention may be applied. In Figure 1, magnetic current loop 100 comprises a conductor having a ring or loop configuration. Magnetic current loop 100 is driven by a current source 102. Current source 102, for purposes of the present invention, is a sinusoidal current source. Figure 2 is a transmission line model illustrating propagation of current around magnetic current loop 100. Propagation of current around a loop conductor driven by a current source can be modeled to a good approximation as a linear transmission line driven at both ends by complementary current sources. In Figure 2, the complementary current sources are generally indicated by reference numerals 102a and 102b. Magnetic current loop 100 can also be divided into sections 104₁ through 104_n for lumped constant modeling purposes, as will be described in more detail below.

Figure 3 is a ladder network illustrating lumped constant modeling of magnetic current loop 100 illustrated in Figure 2. For example, a transmission line can be modeled to arbitrary precision by a lumped constant ladder network representing the series connection of arbitrarily short sections of the transmission line. The shorter the sections, the better the approximation. In Figure 3, each of the sections 104₁ through 104_n includes a series inductance L_s , a series resistance R_s , a parallel capacitance C_p , and a parallel resistance R_p . The series inductance L_s represents the series inductance of each section of the conductor. The series resistance R_s represents the resistance of each section. The parallel capacitance C_p represents the shunt

capacitance of each section, and the parallel resistance R_p represents the dielectric loss associated with the C_p of each section.

Figure 4 illustrates a simplified model of magnetic current loop 100 illustrated in Figure 3. In Figure 4, the dielectric loss represented by R_p is not included because the dielectric loss of a conductor in air is negligibly small. In embodiments of the invention in which current loop 100 is surrounded by a dielectric other than air, the dielectric loss may require consideration. However, for purposes of explanation, the dielectric loss is omitted. Thus, as illustrated in Figure 4, each section 104₁ through 104_n includes series inductance and resistance L_s and R_s , respectively, and parallel capacitance C_p .

Figure 5 illustrates a current loop 100 in which each section 104₁ through 104_n includes reactive compensation according to an embodiment of the present invention. In the illustrated embodiment, the reactive compensation includes n capacitors C_{s1} - C_{sn} . The capacitance value of each of the capacitors is preferably chosen such that the capacitive reactance of each section cancels the series inductance of each section. For example, the capacitive reactance of C_{s1} of section 104₁ preferably cancels the inductive reactance caused by the series inductance L_s of section 104₁. The same is preferably true for the remaining sections of magnetic current loop 100. That is, for each section of magnetic current loop 100, the following expression is

preferably true: $\omega L_{sn} = \frac{1}{\omega C_{sn}}$, where ω is the angular frequency of the current source, L_{sn} is the series inductance of the n^{th} section of magnetic

current loop 100, and C_{sn} is the reactive compensation applied according to an embodiment of the present invention.

Once the series inductance is cancelled, only the series resistance and parallel capacitance of each section remains. Figure 6 illustrates an example 5 of a circuit model of current loop 100 after application of reactive compensation according to an embodiment of the present invention.

In Figure 6, each section 104₁-104_n of magnetic current loop 100 respectively includes series resistance $R_{s1}-R_{sn}$ and parallel capacitance $C_{p1}-C_{pn}$. The parallel capacitance C_p of each section is sufficiently small that the 10 RC phase delay formed with the parallel capacitance C_p and the series resistance R_s is negligible in all but the most extreme cases. The current drive symmetry of current sources 102a and 102b forms two counter-traveling waves of nearly constant magnitudes. The sum of the counter-traveling waves exhibits nearly perfect phase and magnitude uniformity throughout 15 magnetic current loop 100.

Figure 7(a) is perspective view of two magnetic current loops, each divided into a plurality of sections, wherein each section includes reactive compensation according to an embodiment of the present invention. Referring to Figure 7(a), magnetic current loops 100a and 100b are driven by 20 sinusoidal current source 700. Current loop 100a is divided into four sections 701-704. Similarly, current loop 100b is divided into four sections 705-708. Each of the current loops 100a and 100b includes reactive compensation to cancel the series reactance of each section. As discussed above, since 25 inductive reactance may be the dominant component of the series reactance of each section, the reactance added to compensate each section may be

capacitive in nature. More particularly, in current loop 100a, capacitor **C**₁ is added to cancel the inductive reactance of section 703, capacitor **C**₂ is added

to cancel the inductive reactance of section 702, capacitor **C**₃ is added to

cancel the inductive reactance of section 701, and capacitor **C**₄ is added to

- 5 cancel the inductive reactance of section 704. Similarly, in current loop 100b, capacitor **C**₅ is added to cancel the inductive reactance of section 708, capacitor **C**₆ is added to cancel the inductive reactance of section 705, capacitor **C**₇ is added to cancel the inductive reactance of section 706, and capacitor **C**₈ is added to cancel the inductive reactance of section 707.

- 10 When a current loop is divided into sections and reactively compensated such that the series reactance of each section is effectively cancelled, magnitude and phase of the current at any point on the current loop is nearly equal at any given instant and time. As a result, the magnitude and phase on adjacent current loops that are properly reactively compensated is

- 15 also nearly equal. Moreover, since the current flows in one direction in one magnetic current loop and in the opposite direction in the other magnetic current loop, the dipole magnetic fields of the two current loops cancel. As a result, the only far field that remains is the quadrupole field. Since the

quadrupole field decreases proportionally to $\frac{1}{R^3}$, where R is the distance from

- 20 the source, it is possible to increase the power, thereby increasing the near fields without producing a corresponding strong far field that exceeds the appropriate regulatory agencies limit for electromagnetic radiation. Such a configuration is especially well adapted for radio frequency identification devices, as will be discussed in more detail below.

Although the embodiment illustrated in Figure 7(a) includes only two magnetic current loops, the present invention is not limited to such an embodiment. A magnetic current loop system may include any number of magnetic current loops. Suitable magnetic current loop systems to which reactive compensation according to the present invention may be added are described in detail in the above-referenced copending patent applications. Hence, a description thereof will not be repeated herein.

Figure 7(b) is a perspective view of a magnetic current loop system according to an alternative embodiment of the present invention. In Figure 10 7(b) a magnetic current loop system includes first and second magnetic loops 750 and 752 and a third magnetic current loop 754. Each of the magnetic current loops 750, 752, and 754 includes reactive compensation on a per section basis as previously described. In addition, the outer magnetic current loops 750 and 752 are driven by a current source such that current flows in a 15 first direction 756. The inner magnetic current loop 754 is driven by a current source such that current flows in a second direction 758 that is opposite the first direction 756. In addition, the current flowing through inner magnetic current loop 754 is preferably twice that of the identical currents flowing through outer magnetic current loops 750 and 752. In addition, inner 20 magnetic current loop 754 is preferably equally spaced from outer magnetic current loops 750 and 752. In other words, the distances d_1 and d_2 in Figure 7(b) are preferably equal.

Given the configuration illustrated in Figure 7(b), the dipole and quadrupole fields produced by the magnetic current loops cancel at distances 25 far from the magnetic current loops, i.e., more than 1 wavelength from the

magnetic current loop. As a result, only the octupole field remains, which decreases at a rate proportional to $1/R^4$. The system illustrated in Figure 7(b) is not limited to three magnetic current loops. For example, in an alternative embodiment, inner magnetic current loop 754 can be replaced by two

5 magnetic current loops spaced closely to each other. In such an embodiment, the current flowing through each of the two magnetic current loops would flow in the direction 758 illustrated in Figure 7(b) and the current through each of the magnetic current loops would be i , rather than $2i$. In this alternative embodiment, dipole and quadrupole cancellation would still be achieved.

10 Figure 8 is a schematic diagram of a magnetic current loop including reactive compensation according to an embodiment of the present invention in which the compensating reactance is chosen to be slightly off resonance for each section. series reactance series reactance. More particularly, each capacitor $C_{s(k)}$ where $1 \leq k \leq n$ is chosen to be slightly off resonance for its

15 respective section (k), such that the series impedance of the compensated section is $Z_{s(k)} = R_{s(k)} - \frac{j}{\omega C_{e(k)}}$, where $C_{e(k)} = \frac{C_{s(k)}}{1 - \omega^2 L_{s(k)} C_{s(k)}}$ is the effective series capacitance of section (k). The value of $C_{e(k)}$ must be chosen such that $Z_{s(k)}$ of section (k) is a positive real constant $A_{(k)}$ times the parallel impedance $Z_{p(k)} = X_{(k)} Z_p$, where real number $X_{(k)}$ is the effective length of

20 section (k), $Z_p = \frac{R_p}{1 + j\omega R_p C_p}$ is the shunt impedance of a unit length section, and R_p and C_p are parallel resistance and capacitance respectively per unit length of section. Notice that except for $X_{(k)}$, $Z_{p(k)}$ depends only on the dielectric environment of the section. Therefore, the $Z_{p(k)}$ of all sections of a

loop are real valued multiples $X_{(k)}$ of the same complex constant if the loop is in a uniform dielectric environment, such as identical width runs on a printed circuit board. If input impedance $Z_{in(k+1)}$ of section $(k+1)$ is $D_{(k+1)}Z_p$, then input impedance $Z_{in(k)}$ of section (k) is

5
$$Z_{in(k)} = Z_{s(k)} + \frac{Z_{p(k)}Z_{in(k+1)}}{Z_{p(k)} + Z_{in(k+1)}} = \left(X_{(k)}A_{(k)} + \frac{X_{(k)}D_{(k+1)}}{X_{(k)} + D_{(k+1)}} \right) Z_p = D_{(k)}Z_p,$$

where $D_{(k)}$ is a real number. By recursion then, $Z_{in(k)} = D_{(k)}Z_p$ where $D_{(k)}$ is real for all (k) . The current transfer function for section (k) is:

$$F(k) = \frac{Z_p(k)}{Z_{in}(k+1) + Z_p(k)} = \frac{X(k)}{D(k+1) + X(k)}$$

which is real, and which means theoretically that the input and output
10 currents are exactly in phase. Consequently, the phase uniformity of the entire loop may be made arbitrarily good with suitably large choice of n .

Magnetic-Current-Loop-Based Communication Systems

Figure 9 is a block diagram of a radio frequency identification tag reader 900 and a radio frequency identification tag 902 wherein the reader
15 includes magnetic current loops having reactive compensation according to an embodiment of the present invention. In the illustrated embodiment, reader 900 includes driven magnetic current loops 904 and 906. Magnetic current loops 904 and 906 are adapted to couple a radio frequency magnetic field to identification tag 902. Magnetic current loop 908 is adapted to detect a
20 radio frequency magnetic field produced by identification tag 902. Detecting magnetic current loop 908 is preferably located between driven magnetic current loops 904 and 906 and spaced equidistantly from magnetic current loops 904 and 906. Magnetic current loops 904 and 906 produce opposing

magnetic fields such that the dipole fields cancel. Because magnetic current loops **904** and **906** produce opposing magnetic fields, the magnetic field between magnetic current loops **904** and **906** cancels at a distance that is equidistant from magnetic current loops **904** and **906**. Accordingly, locating 5 detecting magnetic current loop **908** equidistant between driven magnetic current loops **904** and **906** minimizes the detection of the signal produced by magnetic current loops **904** and **906** by magnetic current loop **908**.

Reader **900** includes circuitry for processing the field detected from identification tag **902** into usable format. In the illustrated embodiment, the 10 circuitry includes a radio frequency preamplifier **910** for preamplifying the detected field, a down converter **912** for converting the detected field to a signal at a convenient frequency, bandpass filters and amplifier **914** for amplifying and filtering the signal in a band centered at the frequency of the output from down converter **912**, amplitude modulation detector **916** for 15 detecting the amplitude of the signal, and comparator **918** for converting the signal into digital format. RF preamp **910** may be any conventional amplifier circuit that amplifies signals at the frequencies of interest. Down converter **912** may be a conventional mixer that subtracts the frequency of a reference signal produced by an oscillator **920** from the frequency of the detected field. 20 Oscillator **920** may be any type of conventional resonator adapted to produce a signal at a frequency corresponding to the card communication frequency, which may be 13.56 MHz. Bandpass filters and amplifier **914** may include a conventional bandpass filter and an amplifier adapted to amplify the signal about the frequency produced by down converter **912**. Amplitude modulation 25 detector **916** may be a conventional rectifier circuit that detects the amplitude

of a signal. Finally, comparator 918 may be a conventional comparator integrated circuit that produces a digital output based on the relationship between an analog input and a reference value.

On the driving side, reader 900 includes an amplitude modulator 922 and a linear power amplifier 924. Amplitude modulator 922 may be any type of conventional amplitude modulator. Power amplifier 924 may be any conventional amplifier with a gain that is adjusted to produce a magnetic field in a range sufficient to communicate with tag 902 at a distance of at least about 3 meters from current loops 904, 906, and 908.

In operation, reader 900 preferably continuously produces a magnetic field that will power a tag when the tag is brought within a predetermined distance of transmitting current loops 904 and 906. When a tag, such as tag 902, is brought into the range of magnetic current loops 904 and 906, tag 902 rectifies the signal and utilizes the rectified signal to power a microprocessor resident on tag 902. The microprocessor resident on tag 902 amplitude modulates a digital signal on a subcarrier which in turn varies the resonant frequency of its current loop to produce an amplitude modulation of the circulating current. Detecting loop 908 of reader 900 detects the amplitude modulated field from tag 902. RF preamp 910 amplifies the detected field from tag 902. Down converter 912 converts the amplified signal to the subcarrier frequency. Bandpass filters and amplifier 914 filter unwanted components from the signal and amplify the components of interest. AM detector 916 detects the amplitude of the received signal. Finally, comparator 918 converts the signal from the tag into digital format. The digital output from comparator 918 may be processed by a microprocessor resident in reader

900 to perform some useful functions. For example, if tag 902 is located on a product in a manufacturing facility, the information received from the tag may be an identification code or serial number for the product and the microprocessor of reader 900 may store the serial number in memory.

- 5 Another example of information that may be produced by tag 902 is an access code to access a secure facility. In this instance, the microprocessor of reader 900 may grant or deny access.

Because magnetic current loops 904 and 906 include reactive compensation according to embodiments of the present invention, tag 902

- 10 can be read at a distance that is spaced from magnetic loops 904 and 906 without requiring a power increase at reader 900 that violates regulatory limits.

In addition, because the individual sections of magnetic current loops 904 and 906 do not require separate power sources, the circuitry used to drive magnetic current loops 904 and 906 is simplified.

- 15 Although the multi-loop systems described above focus primarily on flowing currents in opposite directions in adjacent magnetic current loops, the present invention is not limited to such an embodiment. For example, in metrology, it may be desirable to drive Helmholtz coils at a high frequency.

Helmholtz coils are of a particular geometry of two circular loops which at DC 20 produce a region about their center where the field and its first spatial derivative are constant which may also be useful to accomplish in the RF band. The currents in the loops preferably flow in the same direction.

Helmholtz coils are often used to cancel the DC magnetic field produced by the earth or other source within some defined volume. High frequency

- 25 Helmholtz coils may be similarly used to cancel out interfering magnetic fields

at a high frequency. Alternatively, it may be desirable to create a high frequency magnetic field having a uniform magnitude within a defined volume.

Accordingly, reactive compensation may be added to current-loop(s) and the current loops may be driven by currents flowing in the same direction

5 to achieve magnetic field cancellation of an externally generated high frequency field, or production of a uniform high frequency magnetic field within a defined volume. Externally generated high frequency magnetic field cancellation may be useful in a laboratory in which it is desirable to have a zero-magnetic field. In this situation, the axes of the Helmholtz coils would be

10 oriented parallel to the magnetic field to be cancelled, and driven by currents flowing in the same direction in order to achieve the cancellation.

It will be understood that various details of the invention may be changed without departing from the scope of the invention. Furthermore, the foregoing description is for the purpose of illustration only, and not for the

15 purpose of limitation—the invention being defined by the claims.